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Methods

Mapping Control of Erosion Rates: Comparing Model and Monitoring Data for Croplands in Northern Germany

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Abstract

Control of erosion rates (CER) is a key ecosystem service for soil protection. It is mandatory for sustaining the capacity, especially of agroecosystems, to provide ecosystem services. By applying an established framework to assess soil regulating services, this study compares two approaches to assess CER provision for 466 ha of cropland in Lower Saxony (Central Northern Germany). In a "sealed modelling approach", the structural and the mitigated structural impact were modelled by applying the Universal Soil Loss Equation (USLE). The second approach uses spatially explicit long-term monitoring data on soil loss rates obtained in the investigation area as an alternative to the USLE-based modelled mitigated structural impact.

Assuming that the monitoring data have a higher reliability than the modelled data, the comparison of both approaches demonstrated the uncertainties of the USLE-based assessment of CER. The calculated indicators based on a sound monitoring database on soil loss rates showed that, due to limitations of the USLE model, the structural impact in thalwegs has been underestimated. Incorporating models with the ability to estimate soil loss by rilling und gullying can help to overcome this uncertainty.

The produced set of complementary large-scale CER maps enables an integrated analyses of CER. In the entire investigation area, the provision of CER regulating ecosystem services was generally high, indicating good management practices. Differences at the field scale and between the different regions can be explained by variations of the structural impact and the management practices.

Keywords

regulating ecosystem service, control of erosion rates, biophysical method, USLE, soil erosion, monitoring

Introduction

Soil plays a fundamental, but until now underrated role within the ecosystem service (ES) approach (Dominati et al. 2010, Robinson et al. 2017, Robinson et al. 2013). The supply of many other ecosystem services depends on healthy soils and their functions, especially the supply of provisioning services in agro-ecosystems. Therefore, soil protection is mandatory for sustaining the capacity of ecosystems to provide ecosystem services, such as water purification, nutrient regulation and food production.

A major threat to soils in Europe is erosion by water and wind (Boardman and Poesen 2006). Soil loss degrades the biophysical structures and processes of ecosystems. In Central European agricultural ecosystems, soil erosion by water accounts for the largest share of soil loss (Panagos et al. 2015). Especially croplands are threatened by various land management activities: farmers execute tillage measures, sow crops and apply pesticides. These management measures lead to temporally bare soils which are especially vulnerable to soil erosion by water.

Within the Common International Classification of Ecosystem Services (CICES 5.1, Haines-Young and Potschin 2017), the ES *control of erosion rates (CER)* describes the reduction of soil loss through the ecosystem. Conceptually, CER is a regulating ES, mitigating a structural impact. Interpreted for CER, the structural impact is the soil loss that would occur when no vegetation covers the ground. Accordingly, the service is provided by plants covering the ground.

Many studies on CER apply the structural and mitigated impact concept and according frameworks to assess the related ES supply (e.g. Fu et al. 2011, Guerra et al. 2014, Guerra et al. 2016, Guerra et al. 2015, Jiang et al. 2018, Syrbe et al. 2017). To model the structural and the mitigated structural impact, most of these studies utilise the empirically derived Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978). The USLE and its adaptions (RUSLE; Renard et al. 1997 and RUSLE2015; Panagos et al. 2015) are widely accepted and the most commonly used models to predict soil erosion (Auerswald et al. 2014). Approaches using the USLE methodology deliver appropriate results in small-scale assessments, e.g. in the European assessment by Panagos et al. (2015). However, the

resulting maps have no ground-truth and USLE is known for providing inappropriate results on larger scales, especially in topographic situations that cause intensive gully erosion (Poesen et al. 2003).

A monitoring study on long-term soil loss by water erosion in Northern Germany (Steinhoff-Knopp and Burkhard 2018) can help to evaluate the reliability of USLE-based approaches to assess CER on a larger scale. Furthermore, the monitoring data can be used for an alternative assessment of CER provision in the monitoring areas.

Accordingly, the objective of this study is the comparison of two different approaches to map and assess the ecosystem service *control of erosion rates.* The general framework for assessing the provision of regulation ES published by Guerra et al. (2014) was used in this study. In the first approach, the actual soil loss was modelled with the Universal Soil Loss Equation (USLE) *(modelling approach)*. In the second approach, we replaced the modelled actual soil loss by monitoring data obtained in 17 years of soil erosion measurement in the field *(measurement approach)*. Thus, the study uses a biophysical ES mapping and assessment methodology by combining a model-based approach with a direct measurement method to quantify and to map ES (as defined in Burkhard and Maes 2017 and by the ESMERALDA*1 project).

Based on both approaches spatially explicit, high-resolution maps of ES supply for 465.5 ha cropland in Lower Saxony (Northern Germany) were generated. The comparison of the maps enables the identification of areas with low CER ES supply. Furthermore, deficits in the used framework and models were identified and discussed.

Material and methods

Conceptual framework

Control of erosion rates (CER) is a regulating ES that mitigates a structural impact. The assessment of the actual service supply is based on the definition of the structural impact. In this study, the conceptual framework for assessing the provision of regulating ES developed by Guerra et al. (2014) was adapted. Fig. 1 provides a graphical summary of the adapted framework, presenting (A) the generalised concept for assessing regulating ES, (B) the specified concept for the ES CER and the implementation into the (C.1) modelling and measurement (C.2) approach.

The *structural impact* in the case of the ES CER is the *potential soil loss* defined as soil loss occurring when no vegetation covers the ground (Fig. 1). Consequently, the missing vegetation would not provide the regulating ES. Topography, soil erodibility and rainfall intensity determine the *potential soil loss*. Ground cover by plants and debris protect the soil and mitigate the structural impact. On cropland, ground cover and thereby the *actual erosion regulation* are determined by management measures (tillage, crop selection, intertillage and crop rotation). The a*ctual soil loss* is equal to the *mitigated structural impact* and is controlled by land management options Guerra et al. 2016. The implementation of

the concept needs modelled or measured data on the *potential and actual soil loss*. This study compares two different approaches to define the *actual soil loss*: In the model-based approach (C.1 in Fig. 1), the *modelled actual soil loss* was calculated by using the USLE. In the measurement-based approach (C.2 in Fig. 1), monitoring data from field measurements was used to define the *measured actual soil loss.* The *potential soil loss* was modelled with USLE in both approaches.

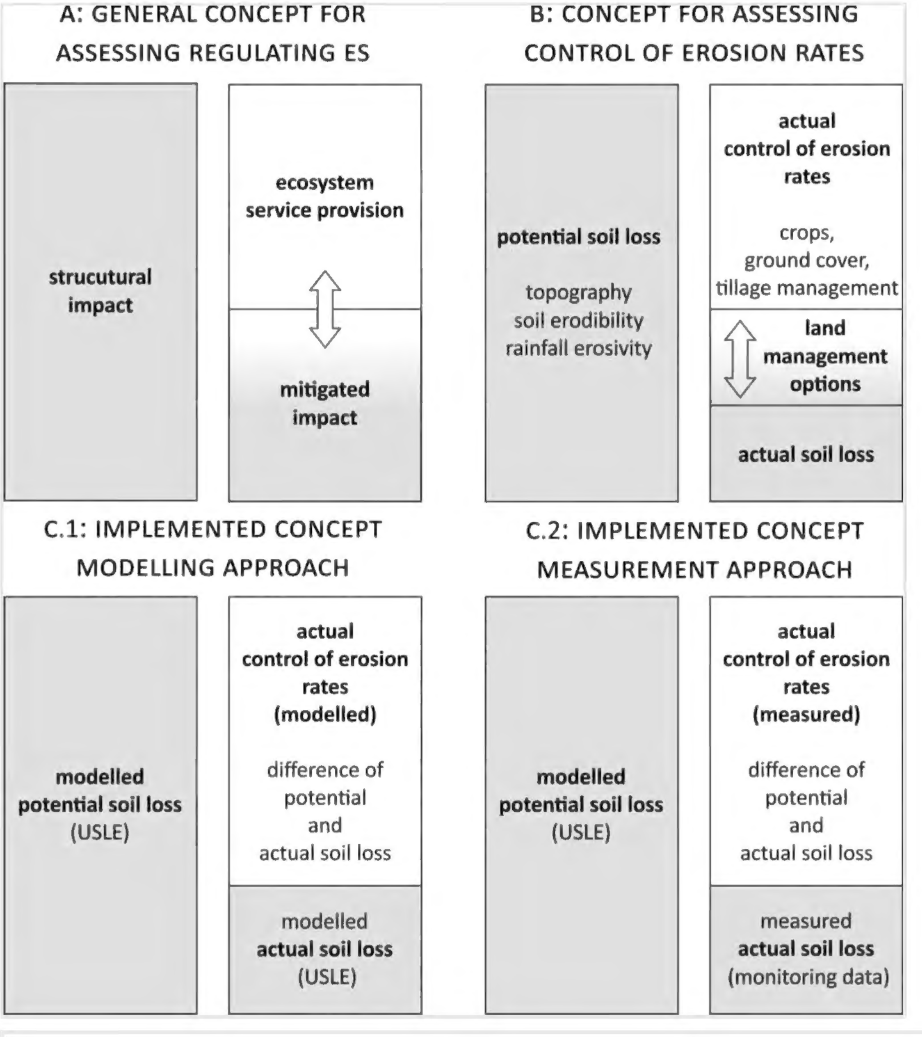

Figure 1.

Applied conceptual framework for assessing the provision of the regulating ES *control of erosion rates* (based on Guerra et al. 2014).

Study area

The study area includes 465.5 ha cropland in three regions of Lower Saxony (Central Northern Germany), representing typical agricultural landscapes with intermediate to high water erosion risk (Fig. 2). All 86 fields are under investigation in the current Lower Saxonian soil erosion monitoring programme (Steinhoff-Knopp and Burkhard 2018). Most soils in the study areas have developed in loess and are highly erodible.

Field size, slope, rainfall, crops and management systems vary between the regions (Table 1). Winter wheat, winter barley and sugar beet are the most important crops in all regions. Maize and potato are relevant in the western and northern region. Most farmers apply soil conservation measures, such as non-plough tillage and mulching.

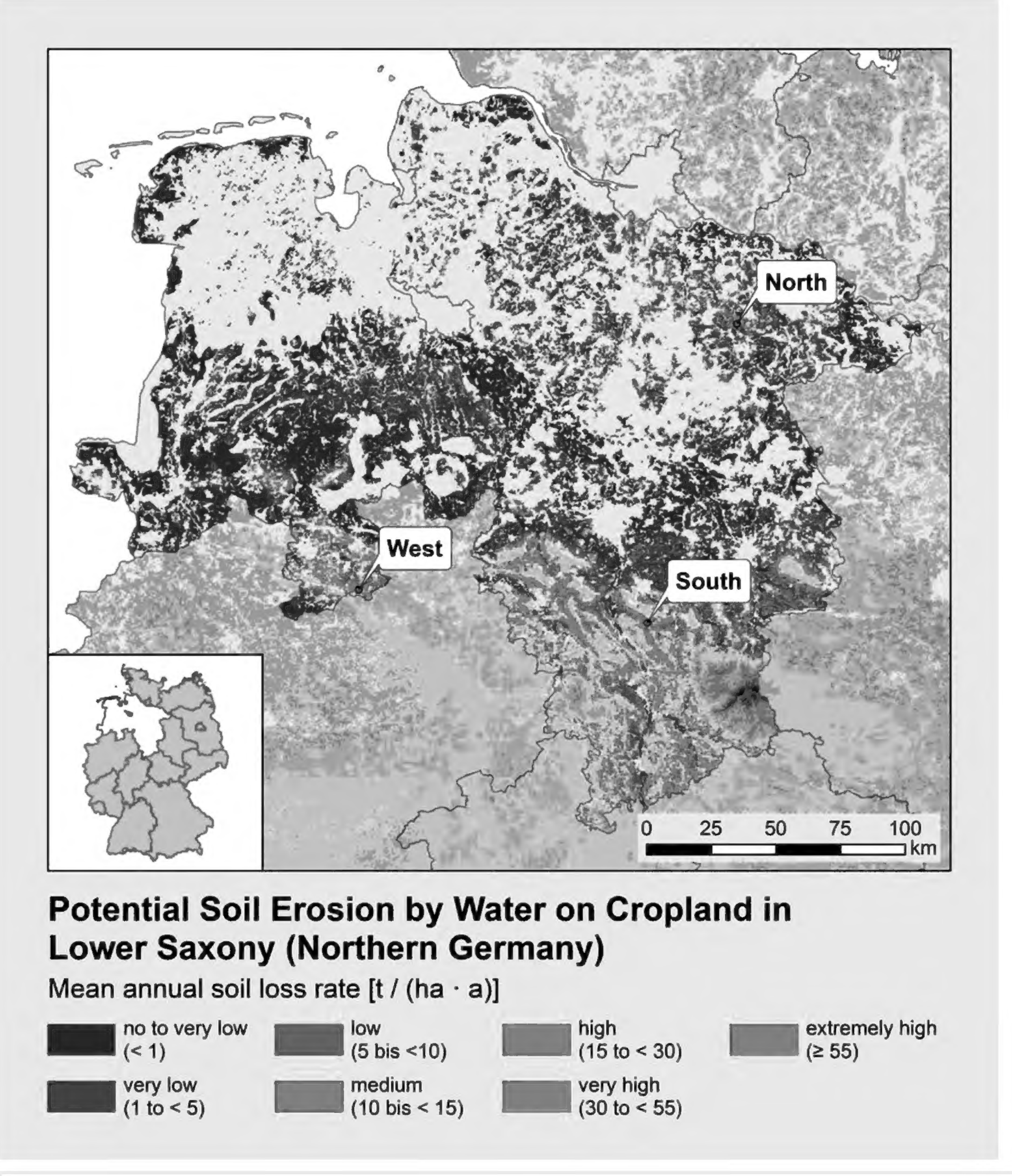

Figure 2.

Potential soil erosion by water on cropland in Lower Saxony (Northern Germany) and location of the investigation regions of this study. Data: Map of the potential erosion risk of agricultural soils by water in Germany (Scale 1 : 1.000.0000). Federal Institute for Geosciences and Natural Resources (BGR) 2014.

Table 1.

Properties of the monitored fields in Lower Saxony, grouped by regions.

Region	*Area [ha]*	*Fields [n]*	*Mean field size [ha]*	*Slope [°] (min / mean / max)*	*Mean annual precipitation (2000 – 2016) [mm]*	*Dominant crops [in order of frequency]*
North	137.7	22	6.3	0.03 / 2.28 / 12.27	721	winter wheat, winter barley, sugar beet, potato
West	28.4	10	2.8	0.03 / 3.58 / 11.47	801	winter wheat, rapeseed, winter barley, maize
South	298.3	54	5.5	0.18 / 4.7 / 15.44	633	winter wheat, sugar beet, rapeseed, winter barley

Monitoring data: Measured actual soil loss

The monitoring data used for the calculation of the mean *measured annual soil* loss rates *(measured mitigated impact)* include 1275 field years and 1355 mapped soil erosion systems obtained from 86 fields in 17 years (2000 to 2016) (Steinhoff-Knopp and Burkhard 2018). The monitoring programme combines the continuous measuring of erosion damage with farmer surveys. The field methods are based on instructions by Rohr et al. (1990) and DVWK (1996). Field measurements were conducted after the winter season and erosive rainfalls (intensities higher than 10 mm h^{-1}).

Quantification of soil loss by linear erosion is the main component of the field surveys. The volumes of rills in the ground caused by flowing water were estimated by measuring length- and cross-sections (depth and width) alongside the channel. Soil losses by sheet erosion were visually estimated according to Ledermann et al. (2010).

The recorded erosion features and their associated soil loss data were stored as geospatial objects. GIS-overlay methods were used to aggregate the monitoring data to a high-resolution map of the mean annual *measured actual soil loss*. Fig. 3 shows exemplary maps of the land use, monitored fields and the *measured soil loss* in t ha^{-1} a^{-1} for two investigation areas.

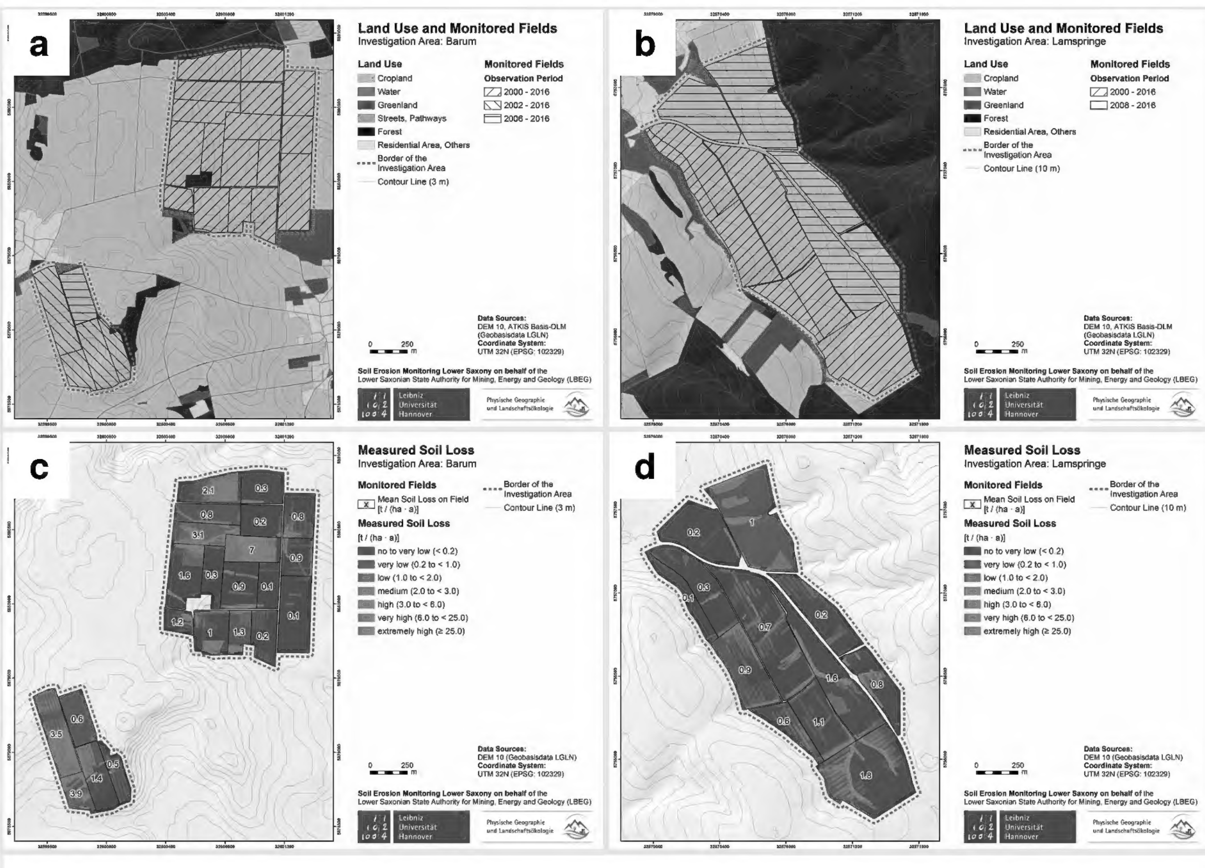

Figure 3.

Maps of the land use and monitored fields and the mean annual *measured soil loss* for the years 2000 to 2016 for two exemplary investigation areas.

a: Land use and monitored fields for the investigation area Barum (northern region).
b: Land use and monitored fields for the investigation area Lamspringe (southern region).
c: Measured soil loss in the investigation area Barum (northern region).
d: Measured soil loss in the investigation area Lamspringe (southern region).

Universal Soil Loss Equation (USLE): Potential soil loss and modelled actual soil loss

Mean annual *potential soil loss (structural impact)* and mean annual *modelled actual soil loss (modelled mitigated impact)* for the years 2000 to 2016 were calculated with the USLE. The German standard of the USLE (Deutsches Institut für Normung e.V. (DIN) 2017) was applied. Loss rates were modelled as raster GIS layers for the 465.5 ha cropland of the study area in a resolution of 12.5 m. The following USLE-equations describe the factors that determine the soil loss rates:

$A_{pot} = R \cdot K \cdot S$ *(potential soil loss)*

$A_{act} = R \cdot K \cdot LS \cdot C \cdot P$ *(modelled actual soil loss)*

A_{pot} and A_{act} represent the mean annual soil loss rate [t ha^{-1} a^{-1}], R the rainfall intensity [N ha^{-1} a^{-1}], K the soil erodibility [t h ha^{-1} N^{-1}] and S [dimensionless] the slope factor. In the formula for the actual soil loss rate, the slope factor S is extended to the topography factor LS (length and slope) [dimensionless]. The factors C [dimensionless] and P [dimensionless] reflect the effects of management and conservation measures. Table 2 lists the data sources used for calculation of the factors.

Table 2.

Origin of data used in USLE-calculations.

USLE-Factor	*Data Source*
Rainfall and runoff erosivity (R)	Weather stations, operated by the Lower Saxonian Authority for Mining, Energy and Geology (LBEG) and Leibniz Universität Hannover (LUH)
Soil Erodibility (K)	Lower Saxonian Soil Map (Scale 1:50 000), Lower Saxonian Authority for Mining, Energy and Geology (LBEG)
Slope (S)	Digital Elevation Model (DEM) 12.5 m resolution, Lower Saxonian Auhority for Geoinformation and Land Survey (LGLN)
Topography (LS)	Digital Elevation Model (DEM) 12.5 m resolution, Lower Saxonian Auhority for Geoinformation and Land Survey (LGLN)
Cover-management (C)	Monitoring data (mapping and farmer surveys)
Conservation measures (P)	Monitoring data (mapping and farmer surveys)

Rainfall and runoff erosivity (R-factor)

The R-factor describes the mean annual erosivity of rainfall and overland water flows. Basically, the R-factor is derived by an analysis of the erosive rainfall events with an intensity higher than 10 mm h^{-1}Wischmeier and Smith 1978). The kinetic energy density of each rainfall event [MJ ha^{-1}] of a year is derived by a formula, multiplied by its maximum 30-minute intensity [mm h^{-1}] and summed up to the yearly R-factor [N ha^{-1} a^{-1}]. Due to high yearly variability, longer periods are needed to derive valid R-factor values.

Alternatively, the R-factor can be calculated with regression equations that describe the relationship between mean annual precipitation and the R-factor. Sauerborn (1994) published equations for Germany that are also incorporated in the German national standard DIN 19709. The following equation, which is valid for the study area, was used:

$$R = 0.0783 \cdot \textit{mean annual Precipitation} - 12.98 \; [\mathrm{N\ ha^{-1}\ a^{-1}}]$$

Values for mean annual precipitation [mm] were provided by four weather stations situated in the investigation areas. Thus, measured weather data for the years 2000 to 2016 could be incorporated.

Soil erodibility (K-factor)

The calculation of the soil erodibility factor is based on a spatially explicit, high-resolution soil map at the scale 1:50 000 (Table 2). The map provides detailed soil information that is needed for the four step calculation of the K-factor as defined by the German national standard method, first published by Auerswald et al. (2014).

1) *for* $f_{Si+vfSa} \leq 70$ %: $K_1 = 2.77 \cdot 10 - 5 \cdot [(f_{Si+vfSa}) \cdot (100 - f_{cl})]^{1.14}$

for $f_{Si+vfSa} > 70$ %: $K_1 = 1.75 \cdot 10 - 5 \cdot [(f_{Si+vfSa}) \cdot (100 - f_{cl})]^{1.14} + 0.0024 \cdot f_{Si+vfSa} + 0.161$

2) *for* $f_{OM} \leq 4$ %: $K_2 = K_1 \cdot (12 - f_{OM}) / 10$

for $f_{OM} > 4$ %: $K_2 = K_1 \cdot 0.8$

3) *for* $K_2 \geq 0.2$: $K_3 = K_2 + 0.043 \cdot (A - 2) + 0.033 \cdot (4 - P)$

for $K_2 < 0.2$: $K_3 = 0.091 - 0.34 \cdot K_2 + 1.79 \cdot K_2^2 + 0.24 \cdot K_2 \cdot A + 0.033 \cdot (4 - P)$

4) *for* $f_{rf} \leq 1.5$ %: $K = K_3$

for $f_{rf} > 1.5$ %: $K = K_3 \cdot [1.1 \cdot \exp(-0.024 \cdot f_{rf}) - 0.06]$

Whereby:

- K K-Factor [t h ha^{-1} N^{-1}]
- $f_{Si+vfSa}$ mass fraction of silt and very fine sand (0.002 – 0.1 mm) in the fine earth fraction [%]
- f_{Cl} mass fraction of clay (<0.002 mm) in the fine earth fraction [%]
- f_{OM} mass fraction of organic matter in the fine earth fraction [%]
- A soil aggregation index (1 to 4), details: Deutsches Institut für Normung e.V. (DIN) 2017
- P permeability index (1 to 6), details: Deutsches Institut für Normung e.V. (DIN) 2017
- f_{rf} fraction of the soil surface covered by rock fragments [%]

Slope (S-factor)

Based on a digital elevation model (DEM) with a raster resolution of 12.5 m (Table 2) , the S-factor was calculated using the following equation first published by Nearing (1997):

$S = -1.5 + (17 / (1 + \exp^{2.3 - 6.1 \sin \alpha}))$

Whereby:

S S-Factor [dimensionless]

α Slope [°], obtained from the DEM

Topography (LS-factor)

The LS-factor was derived from the same high-resolution DEM with 12.5 m raster resolution (Table 2). Differing from the German national standard, the formula proposed by Moore and Burch (1986) was used.

- $LS = (FA \cdot DEM_r / 22.13)^{0.4} \cdot (\sin(\alpha) / 0.0896)^{1.3}$

Whereby:

- LS LS-Factor [dimensionless]
- FA Flow Accumulation, obtained from the DEM
- DEM_r Raster resolution of the DEM
- α Slope [°], obtained from the DEM

Cover management (C-factor)

Detailed management data obtained by the monitoring study was utilised to calculate the C-factor. The C-factor is defined as the “ratio of soil loss from land cropped under specified conditions to the corresponding loss from clean-tilled, continuous fallow” (Wischmeier and Smith 1978). The calculation incorporates the relative soil loss under crops at different growing stages in comparison to soil losses under bare soil conditions at the same time of the year. Accordingly, detailed data on planted crops, their growth and the interannual variation of the rainfall erosivity from the monitoring study were used to calculate the C-factor for the years 2000 to 2017 for every single field of the monitored area. See Wischmeier and Smith (1978) and Deutsches Institut für Normung e.V. (DIN) (2017) for detailed instructions.

Conservation management (P-factor)

The P-factor represents the effect of conservation management measures applied by the farmers, such as cross-slope cultivation, contour farming and strip cropping. The applied German standard version of the USLE (Deutsches Institut für Normung e.V. (DIN) 2017) considers the effects of cross-slope cultivation in dependency of the slope (see Table 3).

Table 3.

P-factor for cross-slope cultivation in dependency of different slope angles. Adapted from Deutsches Institut für Normung e.V. (DIN) (2017).

Slope [%]	**P-factor**
3 to < 8	0.5
8 to < 12	0.6
12 to < 16	0.7
16 to < 20	0.8
20 to < 25	0.9
cultivation in the line of steepest slope	1.0

The effect of cross-slope cultivation is only relevant when the slope length is lower than the critical slope length (SL_{crit}), which is calculated by the following formula:

$$SL_{crit} = 170 \cdot e^{-0.13 \cdot \text{Slope [\%]}}$$

The relevant parameters for the calculations were obtained from the DEM and from farmer surveys on the directions of the tractor tracks on the cultivated cropland.

Indicators for soil erosion and ecosystem service provision

Altogether, five indicators were calculated for the ES analyses, whereof three indicators were applied for the different approaches (*modelled / measured actual soil loss*). Table 4 provides detailed descriptions of the indicators. All indicators were calculated on a raster basis with a resolution of 12.5 m. With regard to the investigation area size of 465 ha, 29241 data points were generated.

Table 4.

Indicators for soil erosion and ecosystem service provision.

Indicator	*Conceptual equivalent*	*Description*	*Unit*
potential soil erosion (SE_{pot})	structural impact	Amount of soil loss when no service is provided.	t ha^{-1} a^{-1}
actual soil erosion (modelled) ($SE_{act,\ mo}$)	mitigated structural impact	Amount of mitigated soil loss when service is provided. Model results based on USLE.	t ha^{-1} a^{-1}
actual soil erosion (measured) ($SE_{act,\ me}$)	mitigated structural impact	Amount of mitigated soil loss when service is provided. Monitoring data obtained in 17 years of field measurements.	t ha^{-1} a^{-1}
prevented soil erosion (modelled) (PSE_{mo})	actual service provision	Amount of ecosystem service provision. Based on USLE model results.	t ha^{-1} a^{-1}

prevented soil erosion (measured) (PSE_{me})	actual service provision	Amount of ecosystem service provision. Based on monitoring data.	t ha^{-1} a^{-1}
provision capacity (modelled) (PC_{mo})	-	Fraction of the structural impact that is mitigated by the actual service provision. Based on USLE model results.	0 to 1 [-]
provision capacity (measured) (PC_{me})	-	Fraction of the structural impact that is mitigated by the actual service provision. Based on monitoring data.	0 to 1 [-]

Results

Potential and actual soil erosion

Table 5 summarises the value ranges and averages for the three indicators describing the structural and the mitigated structural impacts (SE_{pot}, $SE_{act,mo}$, $SE_{act,ma}$), grouped by region. Additionally, Fig. 4 presents two exemplary maps for the three indicators. The mean SE_{pot} for the whole study area (18.41 t ha^{-1} a^{-1}) is significantly higher than the mean for the northern region (12.97 t ha^{-1} a^{-1}). The highest single value for SE_{pot} with 92.07 t ha^{-1} a^{-1} was modelled for a raster cell in the northern region. Average highest values were modelled for the southern region (20.83 t ha^{-1} a^{-1}), whereas the western region shows a slightly lower potential soil loss risk (20.07 t ha^{-1} a^{-1}).

Table 5.

Statistical values for the indicators describing the potential and actual soil loss (SE_{pot}, $SE_{act,\ mo}$ and $SE_{act,\ me}$), grouped by regions [t ha^{-1} a^{-1}] (n = 29181, number of raster cells).

Region	*Indicator*	*Mean*	*Median*	*Min*	*Max*	*SD*
North (n = 8811)	SE_{pot}	11.20	9.20	0.39	86.88	7.44
	$SE_{act,\ mo}$	2.05	1.49	0.00	24.63	1.93
	$SE_{act,\ me}$	1.47	0.23	0.00	49.78	3.00
West (n = 1811)	SE_{pot}	21.99	20.97	1.49	78.28	11.92
	$SE_{act,\ mo}$	2.79	2.40	0.00	18.59	2.27
	$SE_{act,\ me}$	0.73	0.19	0.05	9.29	1.27
South (n = 18559)	SE_{pot}	20.73	19.63	0.64	72.50	9.83
	$SE_{act,\ mo}$	3.37	2.98	0.02	18.93	2.23
	$SE_{act,\ me}$	0.65	0.10	0.00	79.54	2.18
All (n = 29181)	**SE_{pot}**	**17.93**	**16.27**	**0.39**	**86.88**	**10.33**
	$SE_{act,\ mo}$	**2.94**	**2.47**	**0.00**	**24.63**	**2.23**
	$SE_{act,\ me}$	**0.90**	**0.14**	**0.00**	**79.54**	**2.45**

The values for $SE_{act,mo}$ describe the mitigated structural impact modelled by USLE. In accordance with the potential soil loss (SE_{pot}), $SE_{act,mo}$ shows the highest mean (3.37 t ha^{-1} a^{-1}) and median (2.98 t ha^{-1} a^{-1}) values in the southern region. Lowest average values were modelled for the northern region (mean: 2.05 t ha^{-1} a^{-1}, median 1.49 t ha^{-1} a^{-1}).

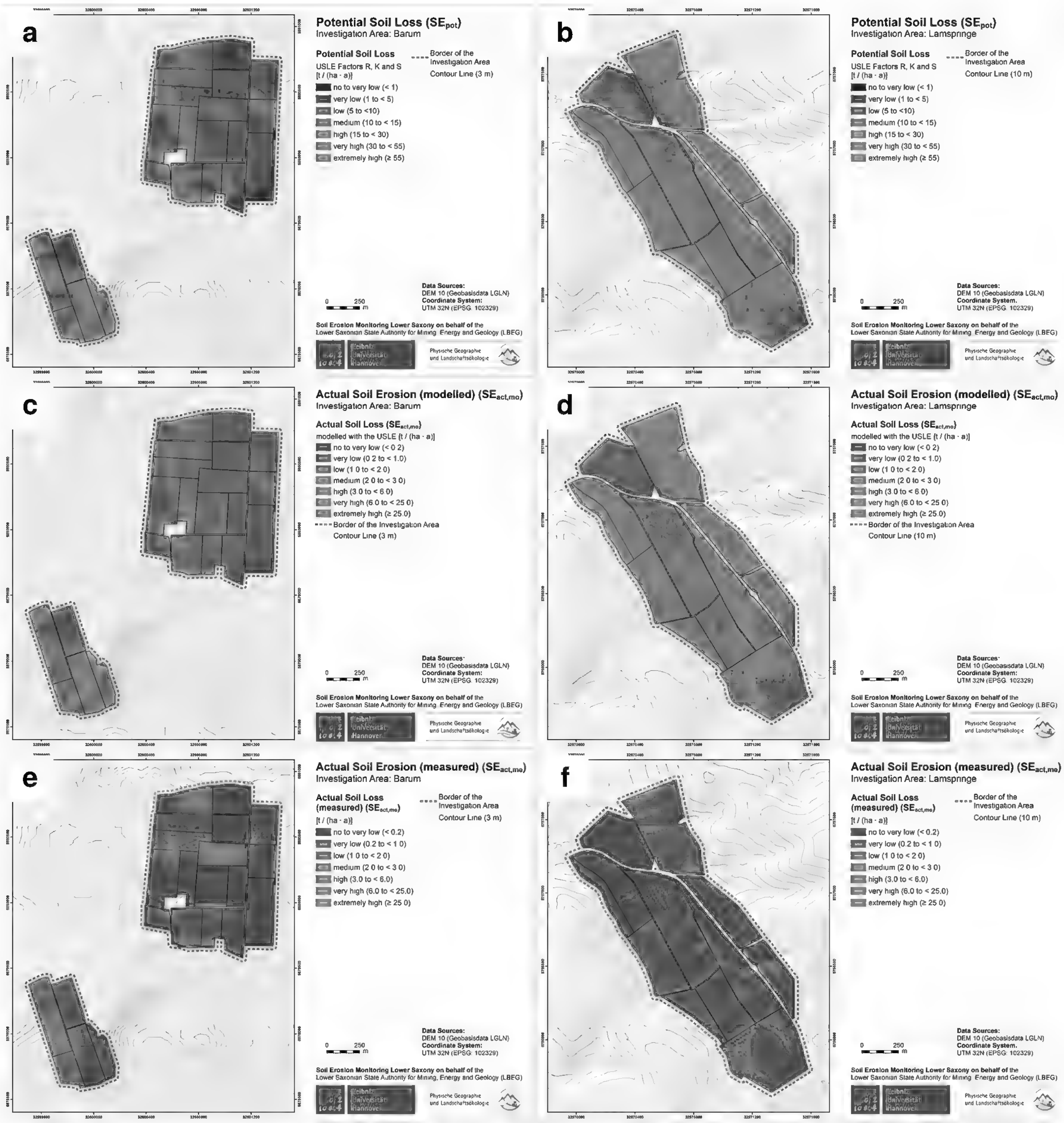

Figure 4.

Maps of potential soil erosion (SE_{pot}), actual soil erosion (modelled) ($SE_{act,mo}$) and actual soil erosion (measured) ($SE_{act,me}$) for two exemplary investigation areas.

a: Potential soil loss (SE_{pot}) in the investigation area Barum (northern region).

b: Potential soil loss (SE_{pot}) in the investigation area Lamspringe (southern region).

c: Actual soil loss (modelled) ($SE_{act, mo}$) in the investigation area Barum (northern region).

d: Actual soil loss (modelled) ($SE_{act, mo}$) in the investigation area Lamspringe (southern region).

e: Actual soil loss (measured) ($SE_{act, me}$) in the investigation area Barum (northern region).

f: Actual soil loss (measured) ($SE_{act, me}$) in the investigation area Lamspringe (southern region).

Overall, the mean of the measured actual soil loss $SE_{act,me}$ (0.90 t ha^{-1} a^{-1}) was significantly lower than the mean of the modelled actual soil loss $SE_{act,mo}$ (2.94 t ha^{-1} a^{-1}). In contrast to the modelled values for SE_{pot} and $SE_{act,mo}$, the measured soil loss $SE_{act,me}$ shows a different regional distribution: the mean (1.47 t ha^{-1} a^{-1}) was highest in the northern region and lowest in the southern one (0.65 t ha^{-1} a^{-1}). The maximum $SE_{act,me}$ value for the whole investigation area was located in the southern region and was 79.54 t ha^{-1} a^{-1} approximately three times higher than the maximum $SE_{act,mo}$ value (24.63 t ha^{-1} a^{-1}).

Fig. 5 shows the differences in the proportion of soil erosion classes between the two indicators for the mitigated structural impact ($SE_{act,mo}$, $SE_{act,me}$). The classes *medium* to *extremely high* added up to a proportion of 58.6% in the modelling approach ($SE_{act,mo}$). The proportion in the measurement approach ($SE_{act,me}$) was 12.3% and significantly lower. The difference in the class *no to very low (<0.2 t ha^{-1} a^{-1})* was extraordinarily high: the proportion for $SE_{act,mo}$ was 1.7% in comparison to 59.8% for $SE_{act,me}$. This finding emphasises that the soil loss measured in 17 years of monitoring was significantly lower than the soil loss modelled by USLE. In contrast, the highest loss class *(extremely high)* was only relevant in the measurement approach ($SE_{act,me}$). Whereby the proportion of 0.2% was still very small and spatially concentrated to areas with intensive rill erosion activity (see Fig. 4e, f).

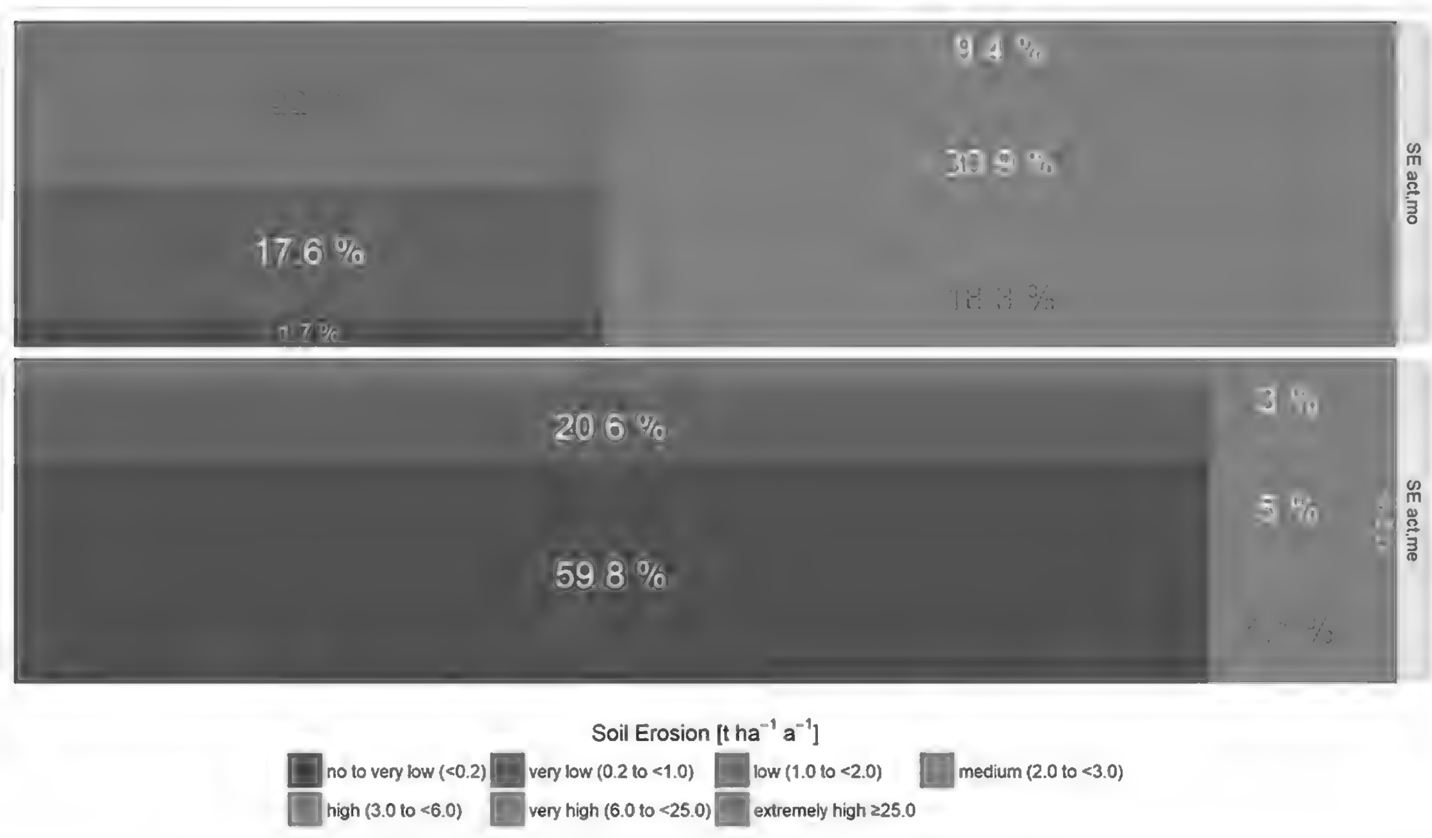

Figure 5.

Area proportions of the soil erosion indicators for the mitigated structural impact ($SE_{act,mo}$: based on modelled actual soil loss data; $SE_{act,me}$: based on measured actual soil loss data). The treemaps visualise the proportions of soil loss classes for the whole investigation area.

Prevented soil erosion

According to the used approach, the prevented soil erosion (PSE) is the amount of actual service provision in t ha^{-1} a^{-1} and defined as the difference between the potential soil erosion (SE_{pot}, modelled by USLE) and the actual soil erosion (SE_{act}). The statistical values for the indicators, PSE_{mo} and PSE_{me}, which represent the *modelling* and the *measurement* approach, were summarised for the three investigation regions shown in Fig. 6 and Table 6. Fig. 7 presents the spatial variety of the indicators for two exemplary investigation areas in maps and Fig. 8 enables the comparison of the areal proportions of the two approaches covered by different PSE-classes.

Table 6.

Statistical values for the indicators describing the prevented soil erosion (PSE_{mo}: based on modelled actual soil loss data, PSE_{me}: based on measured actual soil loss data), grouped by regions [t ha^{-1} a^{-1}] (n = 29181, number of raster cells).

Region	*Indicator*	*Mean*	*Median*	*Min*	*Max*	*SD*
North (n= 8811)	PSE_{mo}	9.15	7.52	0.38	69.01	5.86
	PSE_{me}	9.72	7.66	-38.04	86.82	7.71
West (n = 1811)	PSE_{mo}	19.20	18.34	1.48	68.39	10.37
	PSE_{me}	21.26	20.31	1.35	78.24	11.54
South (n= 18559)	PSE_{mo}	17.35	16.39	0.62	65.73	8.50
	PSE_{me}	20.08	19.06	-59.71	72.41	10.10
All (n = 29181)	$\mathbf{PSE_{mo}}$	**14.99**	**13.40**	**0.38**	**69.01**	**8.83**
	$\mathbf{PSE_{me}}$	**17.02**	**15.44**	**-59.71**	**86.82**	**10.69**

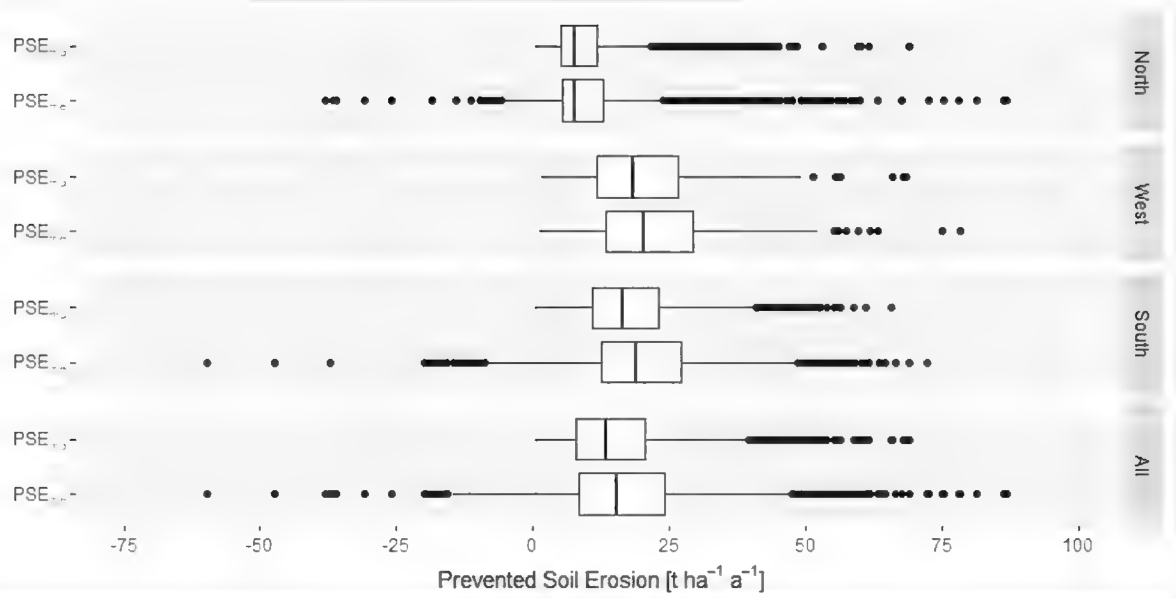

Figure 6.

Boxplots for the indicators representing the prevented soil erosion (PSE_{mo}: based on modelled actual soil loss data, PSE_{me}: based on measured actual soil loss data), grouped by regions [t ha^{-1} a^{-1}] (n = 29181, number of raster cells).

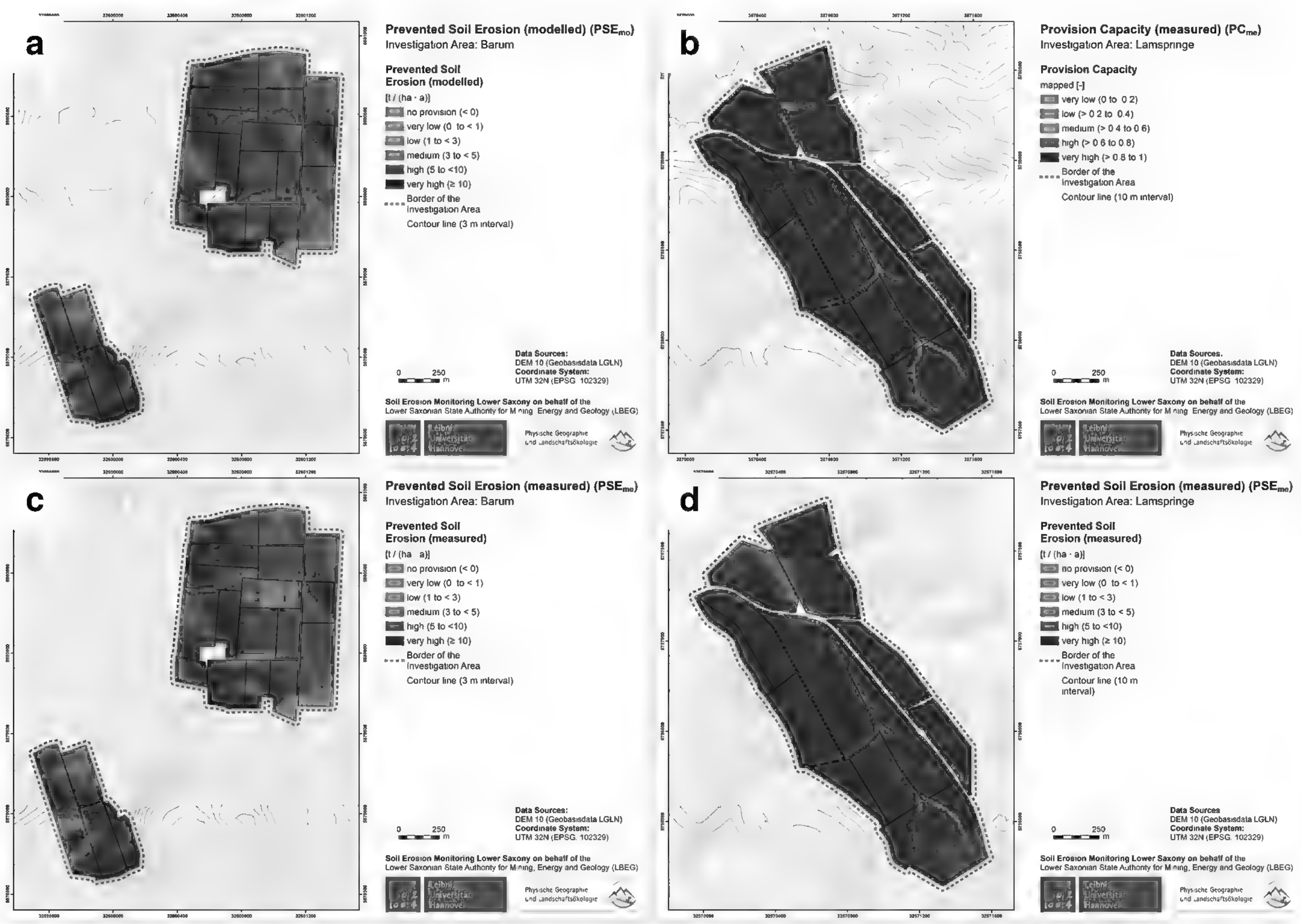

Figure 7.

Maps of prevented soil erosion (modelled) (PSE_{mo}) and prevented soil erosion (measured) (PSE_{ma}) for two exemplary investigation areas.

a: Prevented soil erosion (modelled) (PSE_{mo}) in the investigation area Barum (northern region).
b: Prevented soil erosion (modelled) (PSE_{mo}) in the investigation area Lamspringe (southern region).
c: Prevented soil erosion (measured) (PSE_{me}) in the investigation area Barum (northern region).
d: Prevented soil erosion (measured) (PSE_{me}) in the investigation area Lamspringe (southern region).

The mean PSE for the whole investigation area was 1.14 times higher for the measurement approach (PSE_{me}: 17.02 t ha^{-1} a^{-1}) than for the modelling approach (PSE_{mo}: 14.99 t ha^{-1} a^{-1}). On the regional level, the prevented soil loss was smallest in the north. This result contradicts the finding that the highest maximum values for both approaches were also located in the northern region (Table 6).

The PSE_{me} values lower than 3 t ha^{-1} a^{-1} (classes *no provision, very low* and *low*) cover 4 %, the class *very high* (≥*10* t ha^{-1} a^{-1}) covers 69% of the investigation area (see Fig. 8). In the modelling approach (PSE_{mo}), areas with prevented soil loss lower than 3 t ha^{-1} a^{-1} cover with 2.2% an even lower proportion of the investigation area and also the class *very high* (≥ *10 t ha^{-1} a^{-1}*) was, with a proportion of 65.2%, less common than in the measurement approach.

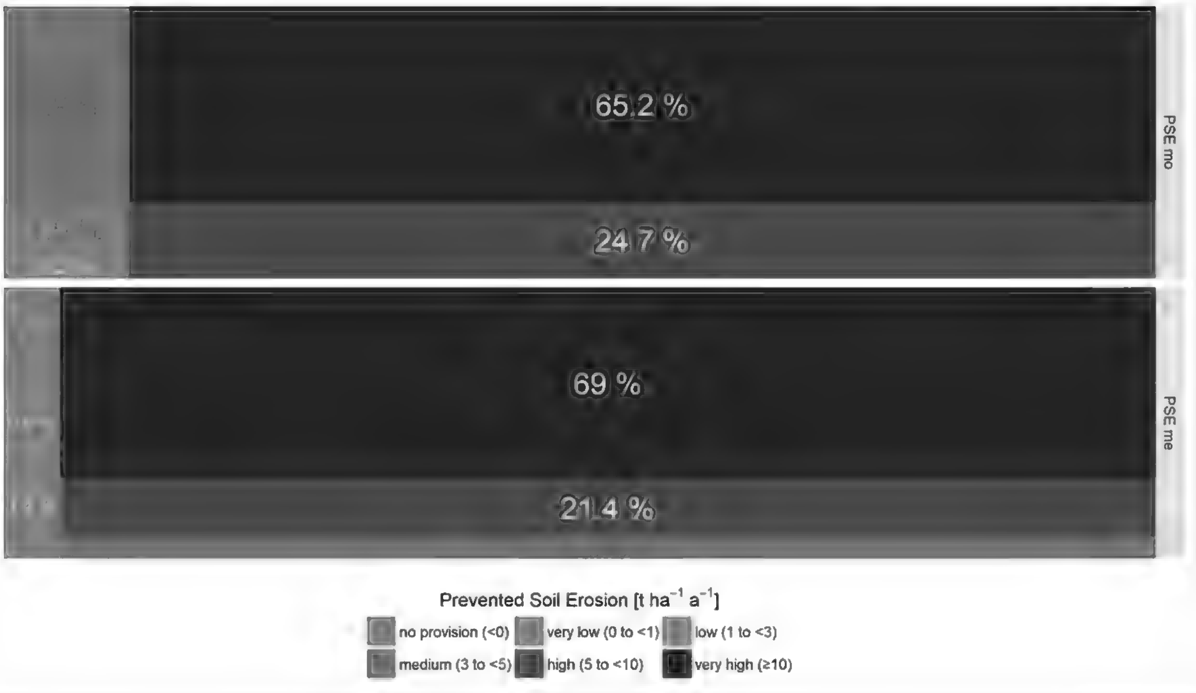

Figure 8.

Area proportions of the soil erosion indicators describing the prevented soil erosion (PSE_{mo}: based on modelled actual soil loss data: based on measured actual soil loss data: PSE_{me}). The treemaps visualise the proportions of soil loss classes for the whole investigation area.

The maps of both approaches depict two important spatial patterns:

a) Areas showing low values of prevented soil erosion (PSE) have also a low potential soil erosion value (SE_{pot}), as the comparison of the south-eastern part of the investigation area Barum in the SE_{pot} map with the PSE maps show (Figs 4a, 7a, c). This can be explained by low values of the structural impact (potential soil loss; SE_{pot}). This result, in combination with the more or less same management measures in each region, in lower values for the mitigated structural impact than in areas with high structural impact.

b) The prevented soil erosion in topographically-defined flow-paths with large contributing catchment areas (thalwegs) was generally lower than in the surrounding areas. This effect was more significant in the PSE values based on the measured actual soil loss data (PSE_{me}; Fig. 7c, d).

Negative values for PSE_{me} in the northern and southern regions (Fig. 6 and Fig. 7c, d) result from measured soil losses that were higher than the modelled potential soil loss (SE_{pot}). The raster cells showing negative PSE_{me} values, falling in the class *no provision* (Figs 7, 8), covered with 6.25 ha just 1.4% of the whole investigation area and were spatially concentrated in areas with intensive rill to gully erosion in thalwegs (Fig. 7c, d). Here the regulation service was definitely too small to adequately mitigate the modelled structural impact. In addition, the used model (USLE) was not able to predict the potential soil loss (structural impact) caused by rilling. The methods used for the calculation of PSE_{mo} was preventing the appearance of negative values. This methodological problem will be addressed in detail in the discussion.

Provision capacity

The provision capacity (PC) is the fraction of the structural impact that is mitigated by the service provision. Theoretically, the PC ranges from 0 (virtually no mitigation by the regulation service) to 1 (complete mitigation of the structural impact).

Both extreme cases occur in the investigation areas: The minimum and maximum for PC_{me} were 0 and 1 respectively. The PC_{mo} maximum was 0.998 (Table 7, Fig. 9). Mean and median of PC_{mo} were 0.838 and 0.851, significantly lower than for PC_{me} (mean: 0.936, median: 0.992). The high mean and medians indicate that most parts of the investigation area are effectively protected against soil erosion by water. This finding is emphasised by the high area proportions of 74.09% (PC_{mo}) and 91.69% (PC_{me}) showing a *very high* provision capacity (PC value: > 0.8 to 1.0) (Fig. 10).

Table 7.

Statistical values for the indicators describing the provision capacity (PC_{mo}: based on modelled actual soil loss data, PC_{me}: based measured actual soil loss data), grouped by regions [t ha^{-1} a^{-1}] (n = 29181, number of raster cells).

Region	*Indicator*	*Mean*	*Median*	*Min*	*Max*	*SD*
North (n= 8811)	PC_{mo}	0.832	0.847	0.399	0.998	0.079
	PC_{me}	0.871	0.981	0.000	1.000	0.232
West (n = 1811)	PC_{mo}	0.884	0.897	0.569	0.998	0.066
	PC_{me}	0.968	0.986	0.629	0.999	0.046
South (n= 18559)	PC_{mo}	0.837	0.948	0.139	0.989	0.084
	PC_{me}	0.964	0.994	0.000	1.000	0.110
All (n = 29181)	$\mathbf{PC_{mo}}$	**0.838**	**0.851**	**0.139**	**0.998**	**0.083**
	$\mathbf{PC_{me}}$	**0.936**	**0.992**	**0.000**	**1.000**	**0.161**

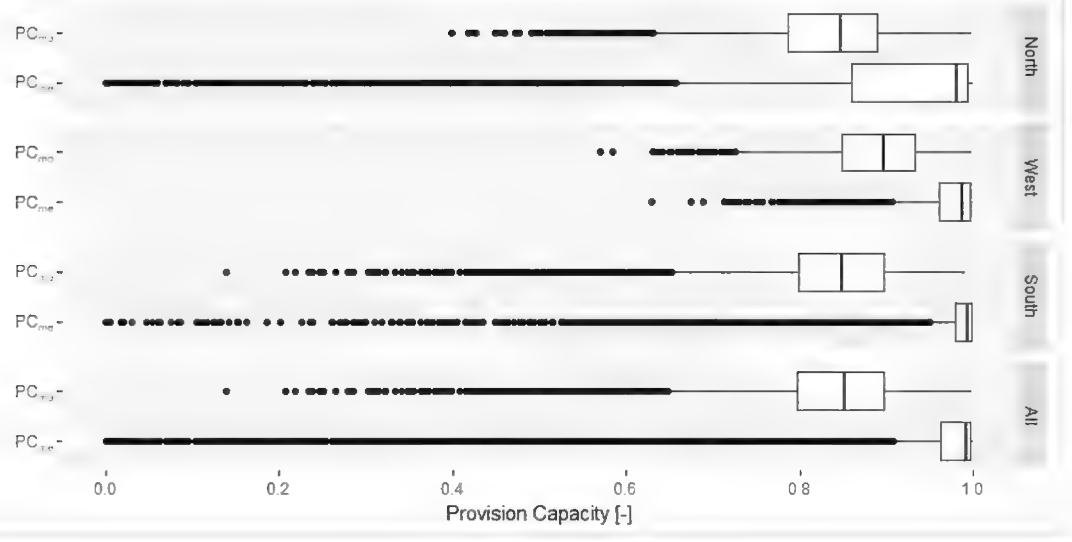

Figure 9.

Boxplots for the indicators representing the provision capacity (PC_{mo}: based on modelled actual soil loss data, PC_{me}: based on measured actual soil loss data), grouped by regions [-] (n = 29181, number of raster cells).

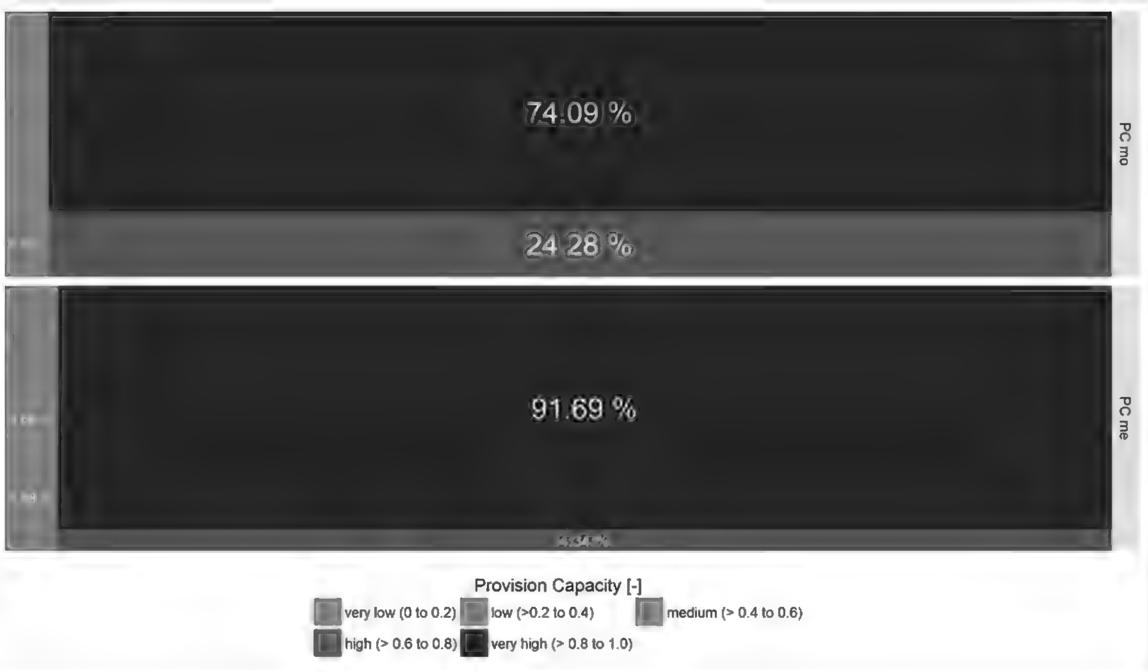

Figure 10.

Areal proportions of the soil erosion indicators describing the provision capacity (PC_{mo}: based on modelled actual soil loss data; PC_{me}: based on mapped actual soil loss data). The treemaps visualise the proportions of the provision capacity classes for the whole investigation area.

Besides the generally high values for PC_{me}, the lowest PC values also occurred in the measurement approach. This is also reflected in the area proportions of the classes *very low provision capacity (<0.2)* of 0% for PC_{mo} and 1.88% for PC_{me} (Fig. 10). This observation coincides with the results for PSE.

Table 7 also exhibits the differences between the investigated regions: in both approaches, the lowest mean PC was calculated for the northern, the highest for the western region, indicating the averaged lowest and highest service provisions for the regions. The boxplots in Fig. 9 give detailed information on the range and distribution of the individual values: the northern region box for the measurement approach indicates a high amount of small PC values and therefore low service provisions. In the modelling approach, the western region showed generally higher values than all other areas. PC_{mo} values lower than 0.4 only occurred in the southern region.

The maps for the modelling approach (Fig. 11a, b) show one important pattern: the provision capacity was lower in areas with larger catchment areas and in thalwegs. Low PCs for one field in the investigation area Lamspringe (Fig. 11b) were based on less erosion mitigating crop rotations and management measures.

The mapping approach resulted in comparable spatial patterns for the provision capacity (Fig. 11c, d). Generally, the area showing values lower than 0.8 was significantly smaller, but values lower than 0.4 were more common. In areas with convergence water flow, the low PC values were concentrated in the central positions of the thalwegs. Fields with larger proportions of low PC_{me} values in the investigation area Barum (Fig. 11c) were affected several times by intensive erosion events when they were planted with potatoes.

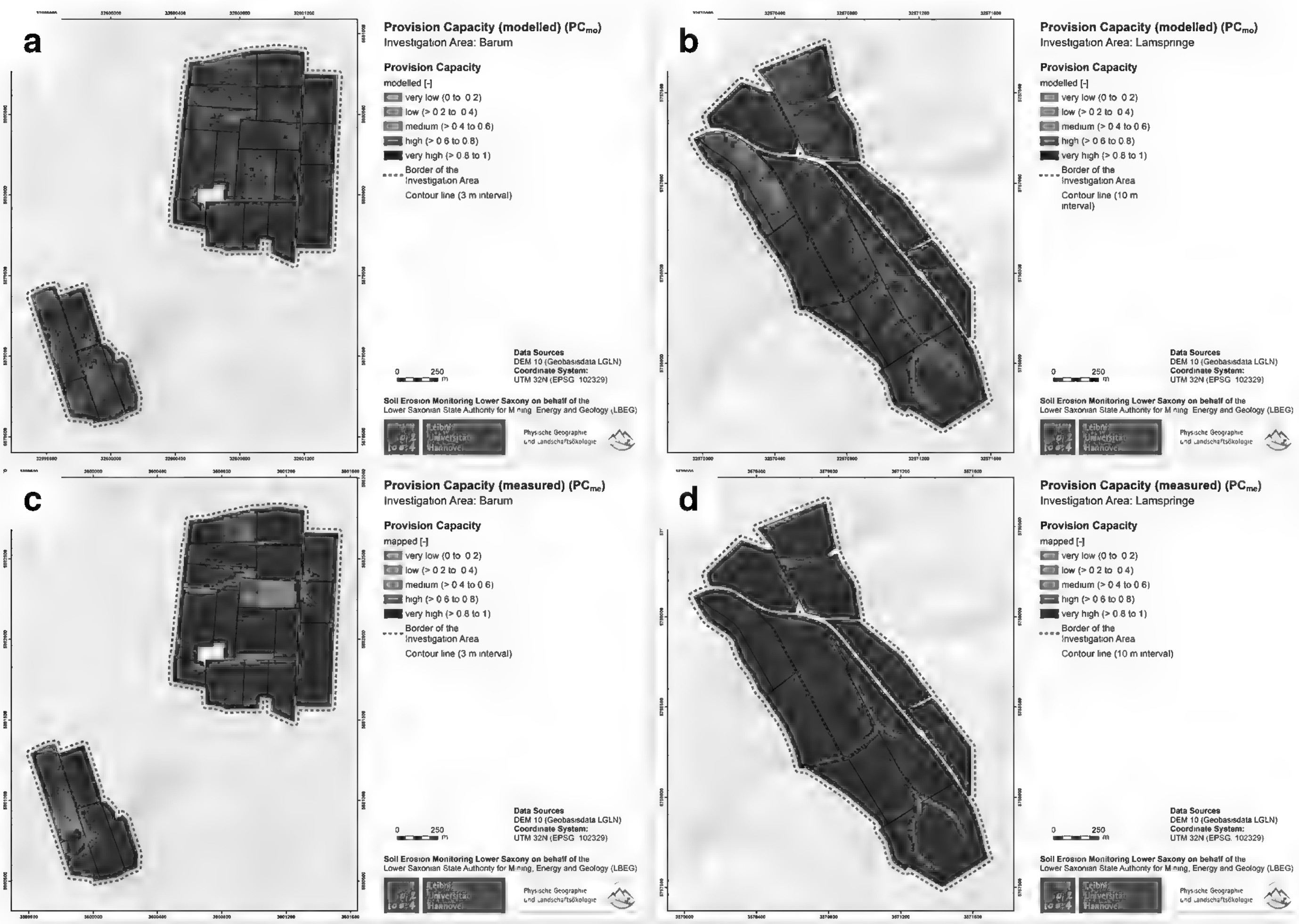

Figure 11.

Maps of the indicators provision capacity (modelled) (PC_{mo}) and provision capacity (measured) (PC_{me}) for two exemplary investigation areas.

a: Provision capacity (modelled) (PC_{mo}) in the investigation area Barum (northern region).
b: Provision capacity (modelled) (PC_{mo}) in the investigation area Lamspringe (southern region).
c: Provision capacity (measured) (PC_{me}) in the investigation area Barum (northern region).
d: Provision capacity (measured) (PC_{me}) in the investigation area Lamspringe (southern region).

Discussion

This study compares two approaches that map the *control of erosion rates (CER)* within an established framework to model regulating ecosystem service supply (Guerra et al. 2016, Syrbe et al. 2017). In general, the long-term monitoring data of the actual soil loss *(measurement approach)* can be considered to be more reliable than the data modelled with USLE *(modelling approach)*. The comparison of both approaches has enabled the analyses of the constraints of the framework.

To keep the results for SE_{pot} comparable with published data for the investigation area, the German standard USLE (Deutsches Institut für Normung e.V. (DIN) 2017) was used. Accordingly, the calculated mean potential soil loss rates of 17.93 t ha^{-1} a^{-1} were similar to the rates published by Umweltbundesamt (2011) and Federal Institute for Geosciences and Natural Resources (BGR) (2014).

Published maps on actual soil loss rates on the state or European level (Saggau et al. 2017, Panagos et al. 2015) utilise agricultural statistics and generalised assumptions to integrate effects of management practices and conservation measures (USLE C- and P-factor). Due to detailed monitoring data, it was possible to consider relevant management and conservation practices for each farmers' field in the study. Therefore, the modelled actual soil loss ($SE_{act,\ mo}$) was in this case more precise and spatially more explicit. The mean value (2.94 t ha^{-1} a^{-1}) and range (up to 24.63 t ha^{-1} a^{-1}) was comparable with the values from other studies in Northern Germany (e.g. Umweltbundesamt 2011, Saggau et al. 2017).

The ES indicator *prevented soil loss (PSE)* showed a generally high service supply with similar results and patterns for both approaches. The mean PSE_{me} of 17.02 t ha^{-1} a^{-1} was 2.03 t ha^{-1} a^{-1} higher than the mean PSE_{mo} (14.99 t ha^{-1} a^{-1}). In the investigation area, the modelling approach tended to underestimate the total regulation service supply.

In the separate approaches, low PSE values coincided with low SE_{pot} values (e.g. in the south-eastern part of Barum Figs 4a, 7a, c). Thus, low PSE values do not imply that the service supply was too low. This emphasises that PSE alone is an inappropriate indicator for the valuation of the actual service supply (Dunbar et al. 2013, Guerra et al. 2016).

The *provision capacity (PC)*, which indicates the fraction of the structural impact mitigated by the ES, is a scaled indicator. It enables the direct comparison of the service supply in different natural settings and the valuation of management practices. The mean *provision capacity* for the modelling approach (PC_{mo} = 0.838) indicated a lower service provision than for the measurement approach (PC_{me} = 0.936). Considering that the measurement approach is based on ground-truth data from long-term field observations (Steinhoff-Knopp and Burkhard 2018), it must be stated that the *modelled actual soil erosion* ($SE_{act,mo}$) was generally too high and did not reflect real conditions very well. Otherwise, 6.25 ha of the entire investigation area showed $SE_{act,me}$ values higher than the SE_{pot}, resulting in negative PSE_{me} values. The areas concerned were mostly located in thalwegs with intensive erosion activity (mostly rilling). Here the USLE, used to model the potential soil loss, underestimated the structural impact.

As stated by Guerra et al. (2016), the combination of complementary indicators supports spatially detailed assessments of the actual ES provision. Especially the high-resolution maps, based on the measurement approach, can be powerful tools to support land management decisions in the investigation areas. They enable the identification of areas with insufficient mitigation of the structural impact: areas in thalwegs and fields with insufficient crop rotations (e.g. with a high proportion of potatoes in the northern region) or with inappropriate management measures (orientation of the cultivation in the line of the steepest slope).

The integrated consideration of the different indicators for the measurement approach enables the assessment of the actual service provision in the different regions of the investigation area. The structural impact and also the prevented soil erosion (based on the measured actual soil loss data) were lowest in the Northern Region (mean SE_{pot} = 11.2 t

$ha^{-1}\ a^{-1}$, mean $PSE_{me} = 9.72\ t\ ha^{-1}\ a^{-1}$). Certainly, the provision capacity (mean PC_{me} = 0.871) indicated a below-average control of erosion rates (mean PC_{me} for the entire study area: 0.938). The highest measured mean soil loss rate of all regions (mean $SE_{act,\ me}$ = 1.46 $t\ ha^{-1}\ a^{-1}$) emphasised this finding and coincided with less sustainable soil management practices than in the other regions and the cultivation of problematic crops such as potatoes. The western and southern regions showed higher values for the structural impact (mean SE_{pot} = 21.99 (west) and 20.73 $t\ ha^{-1}\ a^{-1}$ (south)). The very high provision capacities (mean PC_{me} = 0.968 (west) and 0.964 (south)) and low actual soil losses (mean $SE_{act,\ me}$ = 0.73 (west) and 0.65 (south) $t\ ha^{-1}\ a^{-1}$) indicated an adequate service provision. This finding coincided with the implementation of soil conservation management practices by the farmers in these regions. While the control of erosion rates was generally high in the southern region, the lowest PSE_{me}-values also occurred in these regions. They were located in thalwegs and partially showed PC_{ma} values of zero indicating an insufficient service provision in these areas.

A major methodological problem was the definition of the structural impact. As in other studies (e.g. Guerra et al. 2016, Syrbe et al. 2017), the potential soil erosion (SE_{pot}) was modelled with a derivative of the USLE. A well-known gap in the USLE is the inability of the model to predict soil loss arising from intensive rilling and gullying (Poesen et al. 2003). As stated above, only small areas showed negative PSE_{me} values. This result emphasised that the definition of the structural impact was too low at least in these areas. This problem did not occur in the modelling approach: by definition, the modelled SE_{act} cannot be higher than SE_{pot}. However, the monitoring data proved that SE_{pot} modelled with USLE was too low, at least in thalwegs and other areas with concentrated surface runoff. A combination of the USLE with models to predict soil loss by rilling and gullying in these areas (e.g. Erosion 3D, Schindewolf and Schmidt 2012) could solve the shortcomings in the definition of the structural impact.

Conclusions

This study applied an established framework to compare two spatially explicit methods to assess the actual provision of the regulating ecosystem service *control of erosion rates* for croplands in Central Northern Germany. The evaluation of complementary indicators enabled an integrated assessment indicating a generally high service provision caused by good management practices. These positive results vary slightly between the investigation regions.

The most reliable maps presented in this paper are based on long-term monitoring data (measurements). In comparison to these measurement-based maps, the USLE-based (model) maps tended to overestimate the actual soil loss leading to a lower service provision. The monitoring results are, however, only available for the investigation areas. For the creation of similar maps for other regions, the monitoring results must be generalised and values need to be transferred to comparable natural and agricultural settings.

A key problem in the assessment of the ES CER identified through the incorporation of long-term monitoring data is - at least partly - the insufficient definition of the structural impact by USLE. The integration of models for an appropriate prediction of rill and gully erosion will help to improve the reliability of the structural impact.

As stated by Guerra et al. (2014), the applied framework enables the definition of management thresholds by determining acceptable levels of the mitigated structural impact. With regard to soil erosion, Mosimann (1998) published an appropriate assessment framework that also considers the soil depth. The applications of this kind of assessment could enable - in combination with the assessment of other soil-related ecosystem services and the effect of soil erosion on these services - the evaluation of the entire impact of soil erosion on soils, ecosystems and their services.

Blueprint

The following section documents the study according to the 'blueprint for mapping and modelling ecosystem services' presented in Crossman et al. 2013.

Name of the mapping study

Mapping Control of Erosion Rates: Comparing Model and Monitoring Data for Cropland in Northern Germany

Purpose of the study

- Map and assess the actual provision of the regulating ecosystem service control of erosion rates.
- Compare approaches incorporating model and monitoring data to map the control of erosion rates.
- Evaluating established frameworks and models for the assessment of regulating services.

Location of the study site(s) and biophysical type

Cropland in Central Northern Germany (Lower Saxony)

Study duration

2000 - 2016 (17 years of soil erosion monitoring)

Administrative unit

Investigation areas in the Federal State of Lower Saxony, Germany

Main investigator

Bastian Steinhoff-Knopp; Leibniz Universität Hannover, Institute of Physical Geography and Landscape Ecology

Type of project

Monitoring and research

Funding source

This study is based on field data collected in the Lower Saxonion soil erosion monitoring programme. The monitoring has been funded by the Lower Saxonian State Authority for Mining, Energy and Geology of Lower Saxony (LBEG).

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Endnotes

*1 http://www.esmeralda-project.eu/